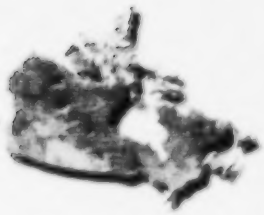

Considering the effectiveness of mountain pine beetle mitigation strategies

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Mountain Pine Beetle Working Paper 2008-21

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Mountain Pine Beetle Working Paper 2008-21

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MPBI Project #8.58

Natural Resources Canada

Canadian Forest Service

Pacific Forestry Centre

506 West Burnside Road

Victoria BC V8Z 1M5

2008

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Printed in Canada

Library and Archives Canada Cataloguing in Publication

Considering the effectiveness of mountain pine beetle mitigation strategies / Nicholas C. Coops ... [et al.].

(Mountain pine beetle working paper ; 2008-21)
"MPBI Project # 8.58".
Includes bibliographical references: p.
Includes abstract in French.
ISBN 978-1-100-112695
Cat. no.: Fo143-3/2008-21E

1. Mountain pine beetle--Control. 2. Mountain pine beetle--Control --British Columbia. 3. Dendroctonus--Control--North America. 4. Mountain pine beetle--Effect of forest management on. 5. Conifers--Diseases and pests --Control. 6. Conifers--Diseases and pests--Monitoring. 7. Conifers--Diseases and pests--Remote sensing. I. Coops, Nicholas C II. Pacific Forestry Centre III. Series: Mountain Pine Beetle Initiative working paper ; 2008-21

SB945 M78 C66 2008 634.9'7516768 C2008-980381-7

Abstract

In this communication, we review a broad range of mitigation strategies associated with the management of mountain pine beetle (*Dendroctonus ponderosae* Hopkins). We consider methods that are currently utilized or proposed for controlling beetle populations, the manner in which the effectiveness of these approaches is monitored and assessed and, finally, the role that remotely sensed data may play in a large-area monitoring system. To this end, we first review the goals of effectiveness monitoring and introduce a general classification system to clarify the purpose and practice of efficacy monitoring. Based on these principles, the review is then structured around effectiveness evaluations for managing forest pests, primarily mountain, southern, and western pine beetles throughout North America. These evaluations are grouped by management strategy: silvicultural treatments; prescribed burns; and the use of attractants, repellants, and insecticides. Finally, we propose the use of remotely sensed data as a complementary tool for monitoring changes in the extent and severity of mountain pine beetle damage across large areas. Use of such data enables assessment of the efficacy of landscape level management practices, direction of the application of new mitigation activities, and reduction of the risk of future infestations.

Key words: mitigation, monitoring, mountain pine beetle, remote sensing, insect, evaluation typology, silvicultural treatment, prescribed burn, attractant, insecticide

Résumé

Dans cette communication, nous passons en revue une vaste gamme de stratégies d'atténuation liées à la gestion du dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins). Nous examinons les méthodes actuellement employées ou envisagées pour contrôler les populations de dendroctones, la façon dont l'efficacité de ces différentes approches est surveillée et évaluée, ainsi que la place potentielle des données de télédétection dans un système de surveillance à grande échelle. À cette fin, nous examinons tout d'abord les objectifs visés en matière de surveillance de l'efficacité, puis nous introduisons un système de classification pour clarifier l'objet et les pratiques de surveillance de l'efficacité. S'appuyant sur ces principes, notre revue s'articule ensuite autour des évaluations de l'efficacité de ces méthodes de gestion en Amérique du Nord des ravageurs forestiers, aux premiers rangs desquels le dendroctone du pin ponderosa, le dendroctone méridional du pin et le dendroctone occidental du pin. Ces évaluations sont groupées par stratégie de gestion : traitements sylvicoles; brûlages dirigés; et en fonction de l'utilisation d'attractifs, de répulsifs et d'insecticides. Finalement, nous proposons l'utilisation de données de télédétection à titre d'outil complémentaire pour surveiller les changements de l'étendue et de la gravité des dommages causés à grande échelle par le dendroctone du pin ponderosa. L'utilisation de ces données permet d'évaluer l'efficacité des pratiques de gestion à l'échelle du paysage, d'orienter l'application de nouvelles mesures d'atténuation et de réduire le risque d'infestations futures.

Mots-clés : atténuation, surveillance, dendroctone du pin ponderosa, télédétection, insecte, typologie des évaluations, traitement sylvicole, brûlage dirigé, attractif, insecticide

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1 Introduction

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestations are currently having a significant impact on the lodgepole pine (*Pinus contorta* Dougl.) forests of British Columbia, Canada. The area affected by the current infestation has been estimated at 9.2 million ha in 2006, compared with 164,000 ha in 1999 (Westfall 2007). In addition, recent research indicates that the beetle is expanding into new geographic areas that were previously considered beyond the beetle's natural ecological range (Carroll et al. 2004). In order to mitigate the economic impacts of the infestation on the forest industry and communities dependent on forestry operations, as well as to reduce the ecological impacts of the infestation, several questions need to be addressed:

- Can the amount of timber lost to the mountain pine beetle be reduced in the short term?
- Can the anticipated impacts of infestations on long-term forest planning and harvesting strategies be addressed?
- Can those strategies that are most effective at reducing both the extent and severity of damage caused by mountain pine beetle populations be identified?

In order to address these questions, information on the location and the extent of mountain pine beetle damage is required. Such information is used for diverse management activities, ranging from strategic planning over large areas to detailed and precise location information for sanitation logging and treatment (Wulder et al. 2004a). Consequently, the scale and methods of current information collection ranges from broad (aerial overview sketch mapping), to more detailed (helicopter Global Positioning System

(GPS) surveys and maps of infested stands derived from aerial photography), to even more detailed ground surveys (Wulder et al. 2006a). Puritch (1981) and Gimbarzevsky (1984) reviewed the application of remote sensing to forest health issues and summarized the state of remote sensing technology up to the early 1980s. In general, their reviews covered a broad range of detection and mapping applications for a variety of forest pests. Aerial photography was identified as the most frequently acquired remotely sensed data type; both true color and color infrared (CIR) photographs were used to map various damage agents, at various scales. The damage agent, scale of photographs, and methods and timing of data collection, influenced the degree to which the forest health studies included in these reviews were successful in fulfilling their objectives (Wulder et al. 2006a). Recent reviews continue to emphasize the utility of aerial photography for surveying damage caused by mountain pine beetle (Ciesla 2000; Roberts et al. 2003).

Generally, when a tree is attacked by mountain pine beetle, the tree's foliage fades from green to yellow to red over the spring and summer following the year of attack (Amman 1982; Henigman et al. 1999). Once the host tree is killed, but still has green foliage, it is in the green attack stage. The first visible sign of impact is a change in foliage color from green to greenish-yellow that usually begins in the top of the crown (Ahern 1988), referred to as *faders*. As the foliage fades from green to yellow to red over the spring and summer in the year following an attack, it gradually desiccates and the pigments break down. This is known as the red attack stage, and it is readily detectable with a variety of remotely sensed data sources, depending on the spatial extent of the damage (Skakun et al. 2003; White et al. 2005, White et al. 2006; White et al. 2007). The final stage, grey attack, follows between 1 – 3 years after red attack and occurs when any remaining

foliage is dead. The rate at which trees progress from green attack through red attack to gray attack is highly variable (Wulder et al. 2006a).

Digital satellite remote sensing offers a complementary methodology for the detection and mapping of mountain pine beetle attack, with the capacity to cover large spatial areas, thereby ensuring a systematic census, rather than a sample, of forest stands (Wulder et al. 2006a). In addition, there is often a reduction in interpreter bias through the application of automated delineation methods (White et al. 2005), which can increase the consistency and reliability of mapping between different areas or dates (Coops et al. 1998; Wulder et al. 2004b). The key to the successful application of remotely sensed data for the detection and mapping of tree mortality caused by mountain pine beetle attack is to match the appropriate sensor and image analysis methods to the information requirements (Wulder et al. 2006b). High spatial resolution imagery, with a pixel size of less than 4 m x 4 m (in multispectral wavelengths) and 1 m x 1 m or less (panchromatic) can provide information related to individual trees or small groups of trees (Wulder et al. 2004b). When collected in multispectral mode, high spatial resolution imagery enables the characterization of individual crowns and therefore is capable of higher accuracy in red-attack mapping than broader based methods (White et al. 2005; Coops et al. 2006a). However, there is a trade-off between higher and broader spatial resolution imagery with finer imagery having a smaller overall image extent and higher cost. At broader scales, Landsat imagery (with a spatial resolution of 30 m) covers a larger area (34,225 km^2); however, individual tree crowns are no longer discernible and mortality caused by mountain pine beetle is represented using stand level statistics (Wulder et al. 2006a).

Control options available for managing the mountain pine beetle depend on the size of the outbreak, the age of the stand, the size of the trees, and the conditions of the site. Generally, control involves a reduction of susceptible and/or infested material in an effort to prevent new attacks. To date, no method has been identified for suppressing an epidemic of mountain pine beetle. The most common management strategies used to reduce or control beetle-induced mortality can be grouped into silvicultural treatments; prescribed burns; and the use of attractants, repellents, and insecticides. In a recent study, Fettig et al. (2007) reviewed factors such as stand density, basal area, and tree diameter and the role these play in bark beetle infestations. They examined several different conifer forest types including ponderosa pine (*Pinus ponderosa)* and lodgepole pine forests and how thinning and prescribed burning can be used as management strategies for beetle-caused mortality reduction. The authors conclude that tree density is correlated with the severity of beetle infestations; this supports thinning as a preventative measure against bark beetle outbreaks. It was also concluded that prescribed burning can be effective but, if improperly carried out, can damage remaining trees to the extent that they become more susceptible to bark beetle attacks.

What is evident from reviewing the literature is that the effectiveness of management strategies is seldom monitored and rarely reported (Stjernberg 2004). It also remains difficult to evaluate empirically how effective a given management strategy has been at reducing local beetle populations, and to compare the efficacy of various control measures. Consequently, once mitigation activities, which include prevention and suppression tactics, have been implemented, the size and the extent of mountain pine beetle populations often remain unknown.

Our primary objective is to review mitigation and efficacy strategies which have been historically applied to beetle expansion, primarily in British Columbia, and more generally, in North America. To achieve this, we collated materials pertinent to the management of mountain pine beetle infestations. First, we assessed the goals of effectiveness evaluation and introduce a general evaluation classification to clarify the purpose and practice of effectiveness evaluations. Based on these principles, we structured the review around effectiveness evaluations for managing forest pests, including mountain, southern (*Dendroctonus frontalis* Zimmermann), and western (*Dendroctonus brevicomis* LeConte) pine beetles throughout North America. These were grouped by management strategy, including silvilcultural treatments; prescribed burns; and the use of attractants, repellants, and insecticides. Attributes or indicators used to evaluate effectiveness were then extracted, assessed and aligned with current remote sensing technologies to determine what the current and future role of remote sensing technology may be in ongoing beetle management programs.

2 Evaluation Classification

The Province of British Columbia's Forest and Range Practices Act (FRPA) describes the Forest and Range Evaluation Program (FREP) which follows the classification scheme of Noss and Cooperrider (1994) for monitoring and evaluation activities. This scheme involves compliance, implementation, effectiveness, and validation.

- Compliance monitoring assesses the degree to which regulations or standards are met.
- Implementation monitoring records rates of progress towards a specific goal (such as rate of adoption of new practices).
- Effectiveness monitoring is used to determine whether the plans or practices implemented are actually meeting the anticipated outcomes.
- Validation monitoring assesses the assumptions upon which forest management strategies, practices and standards are based (Bancroft et al. 2005).

More recently, the World Commission on Protected Areas (WCPA), a branch of the World Conservation Union (IUCN), developed a framework (Table 1) for assessing management effectiveness of both protected areas and protected area systems (Stolton et al. 2003). True effectiveness evaluations focus on measuring outcomes in relation to specific management objectives by asking, "What did we achieve?" (Hawthorn et al. 2002). As such, effectiveness evaluations lend themselves quite easily to empirical investigation (Bingham and Felbinger 2002). By assessing whether actions have produced the desired outcomes, managers are better able to adapt and improve management practices through learning. Evaluation should be seen as a routine part of the adaptive management process (Pomeroy et al. 2004).

Stem et al. (2005) noted that evaluations for measuring effectiveness can be divided into two broad categories: impact assessments are generally one-time assessments, often undertaken when a project is complete, to determine how well the project performed, while adaptive management is an iterative process that involves the integration of project design, management, and monitoring to systematically examine interventions to adapt and learn. Traditionally, forest management has evaluated the success of mitigation actions through the use of impact assessments based on data collected at the end of the treatment to establish how successful (or otherwise) the activity was, when compared to a pre-established control. However, if the cumulative results of these studies were implemented by a forest management agency in order to acquire knowledge and learning and to adapt subsequent management practices, this would be reflective of an adaptive management approach.

3 Literature Review

Studies were compared using a number of criteria including data on beetle population status, as well as specific criteria and indicators used to assess the effectiveness of the approach in relation to stated research objectives for individual studies.

3.1 Silvicultural treatments

The underlying basis for thinning as a mechanism for mountain pine beetle control is based on initial research done in the 1940s on ponderosa pine (*Pinus ponderosa* P.& C. Lawson). These showed that trees were less likely to succumb to attack if their vigour was increased (Eaton 1941). Thinning was therefore proposed as a mechanism to enhance individual tree vigour, which increases the tree's ability to produce resins that are the primary defense against attack. Variations on thinning treatments, including thinning from above or diameter-limit cutting (e.g., Cole and Cahill 1976; McGregor *et al*, 1987) which removes trees over a certain diameter, thinning to reduce basal area (e.g. Amman et al. 1977; Cahill 1978; Bennett and McGregor 1980) which reduces the basal area of the forest to a desired level, and selective removal of trees with thick phloem (Hamel 1978) have all been applied with varying results (e.g., Roe and Amman 1970). Thinning from above generally reduced the susceptibility of mixed or pure stands until residual trees grew to susceptible size, but it also left stands of reduced silvicultural value (Schmidt and Alexander 1985) that were often vulnerable to wind or snow damage. Although thinning from below (which removes trees below a certain diameter) left behind the diameter classes most susceptible to mountain pine beetle attack, mortality was often reduced during outbreaks (e.g., Waring and Pitman 1980; Mitchell et al. 1983).

As thinning research continued, it became apparent that tree vigour was not the sole factor in deterring attack, and the roles of microclimate and inter-tree spacing in the development of infestations required investigation. Amman et al. (1988) suggest that a change in microclimate was the principal factor responsible for reduced attack after thinning because the observed reduction of the mountain pine beetle population often occurred immediately after thinning, while vigour responses might be delayed by "thinning shock" (McGregor et al. 1987; Amman et al. 1988). Thinning from below can therefore optimize the effects of microclimate, inter-tree spacing, and vigour (Whitehead and Russo 2005). To highlight these approaches, we focus on nine published studies which employed a combination of harvesting and thinning practices to manage pine beetle infestations across Canada and the United States. With one exception, all of these studies were established just prior to, or during, a beetle infestation. The exception evaluated the effectiveness of treatment that had been applied 46 years prior to the beetle infestation. Two of the studies focused on a beetle other than the mountain pine beetle, while eight of the studies focused on primary beetle invaders, with only one study focused on secondary bark beetles. Primary beetle invaders are those that will attack a healthy tree, causing stress or mortality. Secondary beetle invaders attack trees that are already stressed from other biotic or abiotic factors. As such, secondary beetle invaders are of much less concern than primary beetle invaders.

Prescriptions for thinning and spacing treatments for beetle management cover a range of targets including thinning stands to spacing of 2 to 6 m (Johnstone 2002; Whitehead et al. 2004; Whitehead and Russo 2005), thinning to 500 trees/hectare (Whitehead and Russo

2005), and removal of two-thirds of the trees from the plot (Hindmarch and Reid 2001). Various forest inventory variables were measured for these studies; they include diameter at breast height (DBH), age (estimated using increment cores), height, and general tree condition. In addition, to assess whether the thinning regime caused differences in stand environments, maximum temperature, wind speed, and solar radiation were measured. In order to assess the effectiveness of the approaches, the ratio of green attacked trees to red attacked trees (G:R ratio); the number of living and dead trees; the presence and amount of coarse woody debris; and the presence of faded crowns, pitch tubes, boring dust (frass), entry/exit holes, and/or parental/larval galleries were all considered. Of these, the number of attacked trees, G:R ratio, and tree mortality were the most common.

Generally, across all the studies, the total number of attacked trees, density of attack, G:R ratio, and tree mortality resulting from mountain pine beetle infestations were lower in thinned and spaced treatments than in untreated stands. Schmitz et al. (1989) found that fewer trees were killed in relation to the number of mountain pine beetles trapped in the most severely thinned stands. Whitehead and Russo (2005) and Whitehead et al. (2004) also found that the total number, density, mortality and G:R ratio of mountain pine beetle attacked trees were much lower in stands that had been thinned. As a result, management guidelines have suggested that thinning mature pine stands from below to a uniform inter-tree spacing of at least 4 m (beetle-proofing) appears to be an effective stand-level treatment, with the treatment best for single layer stands. The thinning is also only effective in the transition between endemic and incipient phases of attack and not during epidemic phases.

Hindmarch and Reid (2001) examined the effects of thinning on two secondary bark beetles: striped ambrosia beetle (*Trypodendron lineatum* Oliver) and pine engraver (*Ips pini* Say). This research found that persistent changes in microclimate following thinning, especially increased wind, were partly responsible for thinned stands having more secondary bark beetles than un-thinned stands. This result is contrary to almost every other study, and Hindmarch and Reid (2001) suggested that the increase in coarse woody debris on the forest floor provides additional habitat for secondary beetles. However, the population dynamics of secondary bark beetles are less influenced by tree vigour, thereby limiting parallels with the mountain pine beetle (Hindmarch and Reid 2001).

Generally, each of the studies examined concluded that thinning or spacing stands was a highly effective mechanism to reduce the abundance and density of pine beetles. Several authors acknowledged the existence of constraining limitations upon the chosen methods, including data collection methods that did not allow for testing the influence of density on attack frequency (Whitehead et al. 2004), variations within and among treatments in site and stand conditions, and the failure to carry out the thinning treatments in a uniform and quantifiable manner. All of these issues made a comprehensive, statistical analysis of the results problematic (Hindmarch and Reid 2001).

Two studies sought to change or reduce the food supply of the mountain pine beetle in treatment plots and to manipulate pine stands to grow at or near optimum site capacity. Cole et al. (1983) used diameter-limit and selective harvesting cuts, and Cole and McGregor (1985) used selective cuts based on diameter at breast height (DBH) and

phloem thickness to reduce or minimize lodgepole pine losses to the mountain pine beetle. Both of these studies utilized several treatments. Cole et al. (1983) applied three general prescriptions: cutting levels based on diameters, selected harvesting, and clearcuts. Cole and McGregor (1985) removed all infested trees and green attack trees that met either specific DBH measurements or phloem thickness criteria. Again, similar forest inventory variables were measured, with tree mortality and pitchouts being the indicators to estimate beetle population dynamics. Both found that the number of infested trees dropped considerably after harvesting, and losses were proportional to the intensity of the cut. According to the rate-of-loss model used in both studies, the selective harvesting (leaving 100 trees) was the best deterrent of recurring infestation, in encouraging regeneration, and in reducing dwarf mistletoe infection.

Schmitz et al. (1989) deployed passive barrier traps at three heights above ground to evaluate mountain pine beetle behavior and abundance in test areas containing two unthinned control stands and five partial cutting treatments: two diameter-limit cuts and three basal area cuts. Percentages of mountain pine beetles caught four years after thinning were significantly greater in the least severely thinned treatment and the unthinned control than in the diameter-limit and basal area cuts, and fewer trees were killed in relation to the numbers of mountain pine beetles trapped in the most severely thinned stands.

According to the Bark Beetle Management Guidebook (British Columbia Ministry of Forests 1995), the most efficient method for dealing with mountain pine beetle over the short term is harvesting, with the objective to remove as much infested wood as possible. Sanitation harvesting targets stands which are actively infested or have a high risk of

continued spread, while salvage logging targets dead trees for the purpose of removing them before they become un-merchantable. Further, additional details that are out of the scope of this communication may be found in Fettig et al. (2007).

3.2 Prescribed burning

The interaction between trees, fire, and insects is complex. Fire damage to trees is often followed by insect or pathogen invasion, which results in fuel build-up and a subsequent return of fire. In such fire-adapted ecosystems, a balance has been maintained between the tree species composition, insect build-up, and pathogen build-up (Parker et al. 2006). Prescribed burning has been used not only to attempt to restore these fire adapted ecosystems, but also to specifically manage bark beetles, control pathogens, and reduce fuel build-up.

Prescribed burning, however, must be carefully considered and planned, as the consequences of an incorrectly applied fire can be significant. In areas where fire has been actively suppressed, the fuel load or stand composition can be such that thinning should be done before burning (Parker et al. 2006). Another consideration is that while a sufficiently severe fire may kill a substantial portion of a bark beetle population, damage to the live tissues of a tree can weaken it enough to make it more susceptible to surviving insects or other pathogens. Thus, prescribed burning should be used judiciously and the impacts on insect and pathogen communities carefully monitored (Fettig et al. 2006, 2007).

Fire is often regarded as an effective beetle management tool; however, there is a dearth of information in the literature regarding monitoring the effects of natural fire on mountain pine beetle infestations. Two studies discussed the use of broadcast burning as an effective management tool. One study baited the study site with synthetic pheromones prior to introducing four burn intensities to determine how intensity affected survival rates of mountain pine beetle broods and establishment of post-burn attack and brood production (Safranyik et al. 2001). The second study involved clearcutting the main infestation area (25 ha) to create a heavy fuel load, followed by prescribed burning to determine the effectiveness of fire in reducing beetle populations (Stock and Gorley 1989). Both studies recorded standard forest inventory and infestation variables including DBH, height to top and bottom of crown, number and life stages of mountain pine beetles, and bole scorch. Both studies effectively achieved their objectives with beetle density inversely proportional to burn intensity; thus, low intensity burns had no effect on beetle survival while beetles had a 0% survival rate in high intensity burns. Beetles were also found to avoid attacking trees showing signs of burning. Stock and Gorley (1989) found that beetle mortality approached 100% in burned plots.

Another option for managing bark beetle using fire is the fall-and-burn treatment described in the Bark Beetle Management Guidebook (British Columbia Ministry of Forests, 1995). This is a direct treatment approach which can be used where resource constraints limit other treatment options, and is effective on smaller patches of infested trees or scattered attack on the edge of larger infestations. According to this approach, trees containing live broods should be felled and the infested portions piled and burned. All infested bark areas must be well burned, and the stumps should be burned or treated

as well. The advantage of this approach is that it can be applied throughout the year, except during fire season.

3.3 Attractants, repellents, and insecticides

The most common strategy reported in the literature for the control of mountain pine beetle populations is the use of attractants, repellents, and insecticides. All of the published studies examined in this review were operational in nature, and initiated following the emergence of a beetle attack, with one exception. Five studies focused on the mountain pine beetle, while nine studied other beetles including the spruce beetle, red turpentine beetle, western pine beetle and southern pine beetle. Four studies focused on more than one beetle species. Three studies focused on the use of anti-aggregation pheromone verbenone only, seven used an attractant/repellent combination, three used an attractant/insecticide combination, and three employed insecticides only. None of the studies we reviewed used just an attractant (e.g., not in combination with either an insecticide or a repellent). Attractants employed in the various studies were *exo*-brevicomin, frontalin/frontalure, myrcene, ipsdienol, lanierone, and *trans*-verbenol. The two repellents used in these studies were verbenon and 4-Allylanisole. Insecticides employed were chlorpyriphos, carbaryl, metasystox-R, fenitrothion, permethrin, esfenvalerate, and cyfluthrin. Only one study used a model (the southern pine beetle spot growth prediction model).

3.3.1 Verbenone only

Three studies examined the use of verbenone, an anti-aggregation pheromone. Typically, verbenone is applied after first being mixed with another material (like wood chips, for example, and then hung from pouches on trees). One of these studies was conducted to determine the efficacy of new *thicker* membrane pouches when compared to standard verbenone pouches (Kegley and Gibson 2004), while the other two studies were conducted to evaluate the efficacy of various densities of verbenone (Payne and Billings 1989; Bentz et al. 1989). Infestation variables that were measured in these studies were rates of spot growth of the infestation; the number of trees classed as green/uninfested; and the number of trees classed as pitchout, strip attacked, mass attacked, and non-host species.

Two of the studies concluded that verbenone successfully protected the trees from beetle attack (Kegley and Gibson 2004; Payne and Billings 1989). The study by Bentz et al. (1989) was not effective in addressing its objectives, as none of the verbenone densities reduced the number of attacked trees; the authors cautioned that the effectiveness of the treatment may have been compromised when above average temperatures followed early placement of the verbenone capsules which then may have degraded before peak beetle emergence.

Borden (1997) reviewed several studies on verbenone, and concluded that on its own it showed inconsistent results in field trials, as some studies showed promising results and others showed little change in bark beetle attack levels. These and other studies (i.e., Amman 1994; Borden 1997; Kostyk et al. 1993; Shea et al. 1992) indicate the

weaknesses of verbenone, including inconsistent results and a breakdown to the inactive compound chysanthenone under ultraviolet radiation (Zhang and Schlyter 2004).

3.3.2 Attractants and repellents in combination

The majority of studies reviewed combined the use of attractants and repellents. Two studies in particular differ from the others in this group as they focused on visual and olfactory disruption of two pine beetles (mountain and southern) using a combination of traps, verbenone, and either the repellent 4-Allylanisole (Strom et al. 1999) or the olfactory disrupter ipsdienol (Strom et al. 2001). Strom et al. (1999) conducted a study to evaluate the importance of visual silhouettes for host finding by southern pine beetles and the potential to disrupt this process using visual deterrents with multi-funnel traps painted white or black. Strom et al. (2001) used funnel traps with verbenone and ipsdienol to evaluate the relative importance of vision in host finding by western pine beetle and the ability to modify the visual stimulus provided by attractant-baited multiple-funnel traps. Infestation variables measured in these two operational studies were total catches of beetles and their major predators (*Thanasimus dubius* and *Temnochila chlorodia*), evidence of mass attack on host tree species, and sex ratio of the target beetle species. Visual and semiochemical treatments, especially used in combination, may increase the effectiveness of bark beetle disruption strategies. Strom et al. (2001) found that white traps also caught far fewer western pine beetles than black traps, but that visual treatments were less effective than olfactory disruptants (verbenone with ipsdienol) which, in combination, resulted in 89% fewer pine beetles being caught.

The other studies used verbenone in combination with one or more attractants. Shore et al. (1992) used verbenone and *exo*-brevicomin. Billings and Upton (1993) used verbenone in combination with frontalin, and Schmitz (1988) and Amman et al. (1989) used verbenone in combinations with *trans*-verbenol, *exo*-brevicomin and myrcene in combination. Only Hayes et al., (1994) used both verbenone and 4-Allylanisole in combination with several attractants: *trans*-verbenol, *exo*-brevicomin, myrcene, ipsdienol, frontalin, and lanierone. Forest variables measured in these studies included tree species composition, diameter at breast height (DBH), total number or percentage of infested trees, basal area of target tree species, stand density, stand types, and location. Measured infestation variables included number of beetles caught by treatment, brood stage at breast height, sex ratio of target beetle and its major predator, and number of major beetle predators caught. In all of the studies examined, verbenone reduced the number of pine beetles caught. Schmitz (1988) compared the influence of the standard lure, with and without verbenone, on mountain pine beetles and found that the addition of verbenone to the synthetic lure reduced the beetle catch by 98%. Amman et al. (1989) used four treatments: verbenone, mountain pine beetle bait, verbenone plus the bait, and a control. The research found a 2.3-fold reduction in the number of infested trees when verbenone was applied to blocks treated with bait. Billings and Upton (1993) found that the combination of felling all trees currently infested and applying verbenone to adjacent standing trees successfully controlled 83% of the 24 treated infestations. Applying verbenone to uninfested pines at the advancing front of single infestations and applying frontalin to uninfested pines in the opposite direction of the same infestation successfully changed the direction of infestation spread in eight of nine treated spots. Finally, Hayes et

al. (1994) found that 4-Allylanisole significantly reduced the catch of beetles at attractant-baited traps.

Volatile profiles vary from one tree species to the next and assist in host selection when bark beetles are in flight. Non-host volatiles (NHV) are compounds that are emitted by non-host trees and essentially reduce bark beetle attraction. The interaction of volatiles and bark beetles is very complex and not fully understood. Several studies have examined the efficacy of verbenone in combination with NHV to reduce attack densities of mountain pine beetle. A combination of verbenone and angiosperm NHV was found to significantly reduce mountain pine beetle attack densities on lodgepole pine (Borden et al. 1998, 2003; Huber and Borden 2001). Despite such promising results, NHV have not been applied operationally for bark beetle control, and more research is needed before the interactions can be fully understood (Zhang and Schlyter 2004).

3.3.3 Insecticides

Three studies examined the efficacy of insecticides for protecting ponderosa pine trees from either the red turpentine beetle *Dendroctonus valens* (Coleoptera: Curculionidae: Scolytinae) or the western pine beetle *Dendroctonus brevicomis* (Scolytinae). Hall et al. (1982) studied carbaryl and chloropyriphos with *exo*-brevicomin, Shea et al. (1984) examined fenitrothion and permethrin in combination with verbenone and *exo*-brevicomin, and Hall (1984) studied carbaryl, chloropyriphos, fenitrothion and permethrin in combination with *exo*-brevicomin, myrcene and frontalin. An attractant was used in these studies for the purpose of ensuring that the baited trees were subjected

to sufficient beetle attack during the study. Infestation variables measured in these studies were the presence or evidence of target beetles and beetle attack, new pitch tubes or boring dust in the bark crevices, and the presence of beetle galleries in dead or dying trees.

These studies were mostly effective at addressing their research objectives. Hall et al. (1982) found that at three months after application, 1% and 2% chlorpyriphos were regarded as ineffective, but that one year after application the low mortality of untreated check trees hindered the determination of efficacy of the remaining four treatments. Shea et al. (1984) determined the efficacy of the insecticide treatment by whether or not the individual tree succumbed to *D. brevicomis* attack after one or two pheromone baiting periods; they found that only the 1% permethrin treatment was regarded as ineffective one month after application and that thirteen months after application only 2% and 4% fenitrothion were still considered to be providing effective protection. Hall (1984) found only 2% and 4% carbaryl and 4% fenitrothion were effective in protecting trees from target beetle attack.

The final three studies included an assessment of the efficacy of insecticides. Werner and Holsten (1992) evaluated the effectiveness of various formulations of carbaryl and diesel in eliminating or reducing brood, parent and callow adult spruce beetles from infested spruce trees. Efficacy of treatments was evaluated for larvae, pupae, and non-emerged and emerged adults. Two percent carbaryl was more effective in providing remedial control of emerged first year and parent adults than non-emerged adults. Two percent carbaryl in diesel and 2% carbaryl in water provided adequate remedial control of second

year emerged adults. Two percent carbaryl in diesel provided the best remedial control of larvae. Carbaryl in diesel and diesel alone caused significantly greater larval mortality (91% and 66% respectively). Carbaryl in diesel caused 50% mortality in first year pupae, but all chemicals tested were ineffective for control of pupae.

Haverty et al. (1996) assessed the effectiveness of the registered application rate of metasystox-R applied with Mauget tree injectors using two strategies: treatment of trees before western pine beetle attack (preventative treatment), and treatment of trees after initial attack by beetle (remedial treatment) on individual, high-value ponderosa pine. Infestation variables measured included foliage sampled at 5, 20 and 40 days after treatment for pesticide residue analysis; samples of phloem and bark tissue collected 20 days after treatment; and the presence of beetle and the verification of galleries and broods in each tree counted as dead or dying. Criterion used to determine the effectiveness of the insecticide treatment was whether individual trees succumbed to attack by western pine beetle and died. Both metasystox-R treatments failed to meet the criterion of efficacy (six or fewer trees killed) as neither treatment was considered effective under mass attack conditions.

In a subsequent study, Haverty et al. (1998) assessed the effectiveness of registered and experimental application rates of insecticides esfenvalerate, cyfluthrin, and carbaryl for protection of individual high-value lodgepole pines from mountain pine beetles in Montana and ponderosa pines from western pine beetles in Idaho and California. Effectiveness was evaluated by determining whether individual trees succumbed to attack by mountain or western pine beetles. In Montana, the lower concentrations of

esfenvalerate were not judged to be effective in protecting lodgepole pine from mountain pine beetle attack, but all three cyflutrhin and both carbaryl treatments were judged highly effective. In Idaho, all treatments were found to be effective in protecting ponderosa pine and in California both esfenvalerate and all cyfluthrin treatments appeared to be effective immediately after treatment.

Monosodium methanearsenate (MSMA) is an insecticide that has shown to be effective in single tree applications. MSMA must be applied within a four week window while the tree is still alive to translocate the insecticide up the bole from the application site. This approach is less labour intensive than felling and burning and is, therefore, generally cheaper provided that it is applied within the time window (Langor 2003). MSMA was used operationally in British Columbia until 2005 when it was no longer available due to a lapse in pesticide registration (British Columbia Ministry of Forests 1995).

4 Discussion

The literature provides a range of options for reducing local mountain pine beetle populations. The effectiveness of these mitigation approaches has been assessed using a variety of attributes, which are generally measured directly through ground-based monitoring programs. Due to the small spatial extent of most of the research studies reviewed for this paper, monitoring using ground-based methods is feasible, effective, and affordable. Operationally, however, the mountain pine beetle has affected vast areas of British Columbia and on the eastern edge of the infestation, in particular, large-scale monitoring is required to prevent the spread of the beetle into Alberta. Such large-scale monitoring requires other data sources to be leveraged in a hierarchical manner: coarse-scale data is used to direct the collection of finer scale data, which, in turn, is used to direct the location of ground-based surveys and mitigation activities. The effectiveness of mitigation activities may subsequently be monitored using a similar hierarchical approach. Remotely sensed data provide a useful complementary data source to facilitate this hierarchical approach and to aid in the allocation of scarce resources for surveillance and mitigation.

As developed by the IUCN and summarized by Stolton et al. (2003), the elements necessary to evaluate the effectiveness of mitigation approaches can be described by six key questions which establish the context, planning, inputs, processes, outputs, and outcomes of a monitoring program (Table 1). Based on the review of the literature presented in the previous section, these questions can be tailored to a programme designed to assess the efficacy of mountain pine beetle mitigation efforts.

4.1 Context: What is the current status of the existing forest and of the mountain pine beetle infestation?

In order to understand the susceptibility of the landscape to mountain pine beetle attack, detailed stand-level forest inventory information is required. The studies examined in this review indicated that the four most commonly measured stand attributes included the dominant species/proportion of stand which is pine dominated, current age of stand, current density of stand, and mean stand DBH and stand basal area. Other supplementary variables collected by at least one of the studies reviewed included the amount of coarse woody debris, size of crown, and increment cores. In addition, several attributes associated with the population dynamics of the mountain pine beetle and related damage caused by the infestation were measured to assess the current status of the damage caused by the beetle. This would include number of attacked trees, G:R ratio, and the number of living and dead trees.

4.2 Planning: What is the target for mitigation efforts?

This question is linked to management and planning objectives, with beetle management occurring at the plot or stand (operational) level, or at the landscape (strategic) level. As discussed above, the information required for these different scales of operation varies. The majority of the reviewed literature focused upon the application of tactics for the suppression of individual infestations. However, when mountain pine beetle populations increase to epidemic levels, they often do so synchronously over very large areas with widespread increases in population levels often exceeding the capacity of forest managers to implement suppression activities over a large area (Carroll et al. 2006). Modelling of beetle populations confirms that if infestation is to be controlled, increasing infestations

must be detected as early as possible. Second, aggressive direct control tactics must be applied promptly and thoroughly. Third, control programmes must be continuous until the desired population level is achieved. If small incipient-epidemic populations increase unchecked, either through lack of detection or as a consequence of incomplete effectiveness monitoring, the probability of successful suppression will decline dramatically, often within only a few years (Carroll et al. 2006). For example, as detailed in Carroll et al. (2006), if the objective of the mitigation is suppression (defined as no net increase in beetle numbers from one year to the next) at a time when beetle expansion is doubling (from an initial population of 10000 infested trees), and 80% of infested trees were successfully treated each year, then it would take 10 years to reduce the infestation to a single infested tree. If a greater proportion of trees could be detected and treated, then suppression would be possible in a shorter period of time. For example, if it were possible to detect and treat 90% of infested trees each year, then it would require either six, eight or 10 years of continuous effort to suppress a population initially infesting 10,000 trees and increasing at a rate of two, three or four times yearly, respectively. The targets for mitigation efforts are therefore clearly critical when planning responses to the outbreak and then subsequently monitoring how effective they were.

4.3 Inputs: What resources are needed to implement the mitigation?

The resources required to reduce the impact of mountain pine beetle infestations vary according to management objectives. Susceptibility to beetle damage can be reduced using a variety of approaches:

- If stands are required to remain in their current structural configuration then attractants, repellents, and insecticides are the required approaches.
- If stands can be altered, then thinning is available.

- If a stand is in a park, or in operable areas, then prescribed burns should be considered.

Consideration should also be given to the resources which are necessary for effectiveness monitoring and what is the number of infested trees that need to be assessed, the risk to surrounding resources, the financial and physical resources available to apply to the strategy, and the potential for success. Each year these factors also need to be re-evaluated to determine if a shift in strategy is required (Caroll et al. 2006).

4.4 Processes: Which mitigation approach should be used?

The most efficient and appropriate way to carry out mitigation activities is somewhat dependent on the objectives and the scale of management. For example, plot level management is most effectively achieved using attractants, repellents, and insecticides, while stand level management of beetle may be more effectively achieved with harvesting and/or thinning regimes. Finally, landscape level management may be undertaken with prescribed burning. In reality, a combination of treatments would likely be required to address mountain pine beetle infestations, depending on the level of attack. Hall (2004) developed a series of strategies to guide forest managers including:

- *suppression/prevention*, where aggressive direct control tactics are applied to reduce populations to endemic levels within a few years (British Columbia Ministry of Forests 1995);
- *holding*, where mitigation is aimed at maintaining population levels at current levels;

- *salvage*, where aggressive mitigation is deemed unlikely to succeed and, therefore, efforts are diverted to recovering dead timber while it still retains value; and
- *monitoring*, where any proactive management options are inappropriate, such as in inaccessible or inoperable regions, parks and protected areas (Hall 2004).

4.5 Outputs: What is the status of the existing forest and the mountain pine beetle infestation after the mitigation is applied?

Of the studies reviewed, the most common data collected to provide information on the impacts of mitigation measures on beetle populations were (in order):

- density of dead trees/density of attack;
- G:R ratio;
- number of faded crowns;
- presence of pitch tubes;
- evidence of boring dust;
- evidence of entry/exit holes;
- evidence of parental/larval galleries;
- phloem thickness;
- rate of spot growth;
- number of beetles; and
- sex ratio of beetles.

In addition, when utilized in an ongoing, adaptive management setting, the program will continue to measure these attributes repeatedly at regular temporal intervals.

4.6 Outcomes: Was the mitigation approach applied successful at reducing the beetle population and/or reducing damage caused to forest stands?

This question is addressed through efficacy monitoring. The attributes measured after mitigation measures have been applied provide an indication of whether changes in stand structure have reduced susceptibility to attack and, furthermore, whether mitigation efforts were successful at reducing beetle populations.

5 Remote Sensing in Efficacy Monitoring of Mountain Pine Beetle Mitigation

The degree to which remote sensing can play a role in monitoring the effectiveness of mitigation approaches to reduce mountain pine beetle populations and subsequent forest damage is dependent on the spatial scale of management, the nature of the mountain pine beetle population (e.g. endemic, incipient, epidemic) and the mitigation approach applied. When considering the application of remote sensing imagery, image characteristics such as the spatial and spectral resolution are important considerations.

5.1 Spatial resolution

The spatial resolution of a remotely sensed scene provides an indication of the size of the minimum area that can be resolved by a detector at an instant in time (Strahler et al. 1986; Woodcock and Strahler 1987). The information content of a pixel is tied to the relationship between the spatial resolution and the size of the objects of interest on the Earth's surface. If trees are the objects of interest and a sensor with a 30 m spatial resolution is used, many objects (trees) per pixel can be expected, which limits the utility of the data for characterizing the individual trees. However, if forest stands are the objects of interest, and an image source with a 30 m pixel is used, a number of pixels will represent each forest stand, resulting in an improved potential for characterization of stand level attributes.

Therefore, it follows that the use of remote sensing imagery in the efficacy of mountain pine beetle treatments will be dependent on the spatial resolution of the remote sensing device used. At the individual tree or plot level, where attractants, repellents, and

insecticides are typically employed, a remote sensing technology which is capable of individual tree detection is required. This type of imagery is acquired by the IKONOS or Quickbird satellites or, as an alternative, by scanned aerial photography. Kneppeck and Ahern (1989) utilized a Multi-detector Electro-optical Imaging Scanner (MEIS–II) and demonstrated that high spatial resolution imagery could be used to detect and map red attack damage with accuracies similar to that achieved by aerial photography. More recently, White et al. (2005) utilized an unsupervised clustering technique on 4-metre multi-spectral IKONOS imagery to detect mountain pine beetle red attack at sites with low and medium levels of attack and compared the estimates to red attack damage interpreted from aerial photography. The results indicate that within a one-pixel buffer (4 m) of identified damage pixels, the accuracy of red attack detection was 70.1% for areas of low infestation (stands with less than 5% of trees damaged) and 92.5% for areas of moderate infestation (stands with between 5% and 20% of trees damaged). Similarly, Coops et al. (2006a) employed Quickbird imagery and found a reasonable correspondence between the number of trees per plot which had red attack damage and the number of pixels detected as unhealthy crowns. Heli-GPS surveys are considered by the British Columbia Ministry of Forests and Range to be the "operational benchmark for accuracy, delivery time and cost for detailed aerial surveys" and are estimated to be spatially accurate to within ± 20 m. Nelson et al. (2006) assessed the accuracy of heli-GPS survey points with concurrently collected field data, and found that 92.6% of the heli-GPS survey points had errors of ±10 trees.

At coarser spatial resolutions, detection of mountain pine beetle mitigation occurs at a stand level. Landsat Thematic Mapper (TM) imagery can be used (along with other

digital geographic data such as elevation, slope, aspect, and incoming solar radiation, where appropriate) to accurately detect mountain pine beetle red attack damage in forest stands with typical accuracies ranging from 70% to 85% (Franklin et al. 2003; Skakun et al. 2003; Coops et al. 2006b; Wulder et al. 2006b); however, this is an estimate of the probability of red attack damage within a pixel, not individual crown counts of unhealthy trees. Skakun et al. (2003) utilized multi-temporal Landsat-7 Enhanced Thematic Mapper (ETM) imagery acquired on three separate dates. A vegetation wetness index for each date was thresholded and a difference index was used to interpret spectral patterns in stands with confirmed red attack damage. The classification accuracy of the red attack damage based on this type of transformation ranged from 67% to over 78% correct (Skakun et al. 2003). Where silvicultural approaches to mitigation such as stand thinning are applied, remotely sensed data can be used to characterize changes in stand structure (e.g. LIDAR), and to assess changes in damage levels over time (e.g. QuickBird, Landsat) (Coops et al. 2006b; Wulder et al. 2006c).

5.2 Spectral resolution

In addition to spatial resolution, the spectral resolution of a sensor can be an important issue for monitoring mountain pine beetle. Spectral resolution provides an indication of the number and the width of the spectral wavelengths of a particular sensor. Sensors with more bands and narrower spectral widths are described as having an increased spectral resolution. Currently, most operational remote sensing systems have a small number of broad spectral channels: Landsat ETM+ data has seven spectral bands in the reflective portion of the electromagnetic spectrum and one band in the thermal-infrared region. Similarly, Quickbird and IKONOS both have four spectral bands in the visible and near

infrared region. By changing the number or spectral width of the spectral bands, characteristic reflectance properties of the surface may be more accurately portrayed, however, as demonstrated by White et al. (2007), even hyperspectral satellite remotely sensed data did not adequately separate low levels of red attack infestation from healthy stands at 30 m spatial resolution due to the considerable natural variability of pine stands.

5.3 Remote sensing as a tool for mitigation activities

The detection accuracies and limitations listed above provide some context for the application of remote sensing technology to aid in mitigation activities. Presently, remotely sensed data has demonstrated capability for identifying the location and extent of mountain pine beetle red attack damage (Wulder et al. 2006a) and different data sources may be selected based on the level of detail required and the phase of the mountain pine beetle population. Unfortunately, red attack damage manifests once the tree has already died, and the beetles have gone on to produce another generation (and potentially migrated to another area). Therefore, monitoring that relied exclusively on this type of information would not facilitate the pre-emptive treatment necessary for direct control of beetle populations (Carroll et al. 2006). However, since green attack is often spatially associated with red attack, and since remotely sensed data can be used to affordably and repeatably monitor large areas, there is a role for remotely sensed data to play in monitoring programs.

For efficacy monitoring at an individual tree or plot level, where attractants, repellents, and insecticides are typically employed, remote sensing technology is greatly limited. If detection accuracy is required to be in excess of 80%, such as recommended by Caroll et

al. (2006), then even the most promising techniques cannot meet this target within a standard level of statistical significance. The true capacity of the technology therefore occurs at landscape levels, where either mitigation techniques require changes to forest structure, such as tree density, or for assessment of the impact of large scale disturbances such as fire. As noted by Hall (2004), remote sensing options are likely to be cost effective and appropriate in the salvage and monitoring phases. In both of these examples, the detection of beetle-related damage is not critical; rather, it is the structure of the trees themselves which needs to be monitored and which can be undertaken more effectively.

6 Conclusion

The current outbreak of mountain pine beetle in British Columbia is having a significant impact on the forest industry and forest dependent communities. Moreover, the ecological effects of the outbreak have not yet been fully realized on the forest resource. Since the size and extent of the current outbreak defies any form of control, interest has shifted to how similar outbreaks may be avoided in the future. A number of mitigation approaches have been tested and evaluated. Few of these approaches have been assessed for effectiveness over time, and even fewer have been documented in the literature. Monitoring the effectiveness of mitigation measures is critical to ensure beetle populations are within those targets set for the mitigation action, and also to ensure that scarce resources are put towards those mitigation measures which are most effective and appropriate for controlling beetle populations. Such monitoring programs, once implemented, also reduce the risk of future infestations by providing constant surveillance of forest conditions. This review provided an overview of the methods that are currently proposed to control beetle populations, the manner in which the effectiveness of these approaches is monitored and assessed and, finally, the role which remotely sensed data may play in this effectiveness monitoring. We propose that there is a role for remotely sensed data in monitoring, as part of a broader multi-scale data hierarchy.

7 Acknowledgements

This project is funded by the Government of Canada through the Mountain Pine Beetle Initiative, a program administered by Natural Resources Canada, Canadian Forest Service. Additional information on the Mountain Pine Beetle Initiative may be found at: http://mpb.cfs.nrcan.gc.ca. We are grateful to Steve Gillanders (UBC) for editorial assistance and the thoughtful comments of the three anonymous reviewers.

8 Literature Cited

Ahern, F.J. 1988. The effects of bark beetle stress on the foliar spectral reflectance of lodgepole pine. International Journal of Remote Sensing 9:1451-1468.

Amman, G.D. 1982. The mountain pine beetle - identification, biology, causes of outbreaks and entomological research needs. Pages 7-12 *in* Proceedings of the Joint Canada/USA Workshop on Mountain Pine Beetle Related Problems in Western North America. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. Victoria, British Columbia, Canada.

Amman, G.D. 1994. Potential of verbenone for reducing lodgepole and ponderosa pine mortality caused by mountain pine beetle in high-value situations. Pages 33-37 *in* P.J. Shea (editor). Proceedings of the Symposium on Management of Western Bark Beetles with Pheromones: Recent Research and Development. US Forest Service General Technical Report PSW-GTR-150.

Amman, G.D.; McGregor, M.D.; Cahill, D.B.; Klein, W.H. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in the Rocky Mountains. USDA Forest Service Gen. Tech. Rep. INT-36. Intermountain Forest and Range Experiment Station, Ogden, UT. p 22.

Amman, G.D.; McGregor, M.D.; Schmitz, R.F.; Oakes, R.D. 1988. Susceptibility of lodgepole pine to infestation by mountain pine beetles following partial cutting of stands. Canadian Journal of Forest Research 18:688-695.

Amman, G.D.; Their, R.W.; McGregor, M.D.; Schmitz, R.F. 1989. Efficacy of verbenone in reducing lodgepole pine infestation by mountain pine beetles in Idaho. Canadian Journal of Forest Research 19:60-64.

Bancroft, B.; Zielke, K.; Kremsater, L.; Bradford, P.; Barber, F.; Thompson, R. 2005. Effectiveness evaluations: A primer for making them truly effective. A workshop summary document. [cited 2007 Jan 31]. http://www.for.gov.bc.ca/hfp/frep/about/types.htm.

Bennett, D.D.; McGregor, M.D. 1980. A demonstration of basal area cutting to manage mountain pine beetle in second growth ponderosa pine. USDA Forest Service Northern Region, Forest Pest Management Report 88-16. 5 p.

Bentz, B.; Lister, C.K.; Schmid, J.M.; Mata, S.A.; Rasmussen, L.A.; Haneman, D. 1989. Does verbenone reduce mountain pine beetle attacks in susceptible stands of ponderosa pine? USDA Research Note RM-495. 4 p.

Billings, R.F.; Upton, W.W. 1993. Effectiveness of synthetic behavioral chemicals for manipulation and control of southern pine beetle infestations in East Texas. USDA Forest Service, Southern Forest Experiment Station. General Technical Report: 555-568.

Bingham, R.D.; Felbinger, C.L. 2002. Evaluation in practice: A methodological approach, New York/Chatham House.

Borden, J.H. 1997. Disruption of semiochemical-mediated aggregation in bark beetles. Pages 421-438 *in* R. T. Cardé and A. K. Minks (eds.), Pheromone Research: New Directions, Chapman and Hall Co., New York.

Borden, J.H.; Wilson, I.M.; Gries, R.; Chong, L.J.; Pierce, H.D. Jr; Gries, G. 1998. Volatiles from the bark of trembling aspen, *Populus tremuloides* Michx. (Salicaceae) disrupt secondary attraction by the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae). Chemoecology 8:69-75.

Borden, J.H.; Chong, L.J.; Earle, T.J.; Huber, D.P.W. 2003. Protection of lodgepole pine from attack by the mountain pine beetle *Dendroctonus ponderosae* (Coleoptera: Scolytidae) using high doses of verbenone in combination with nonhost bark volatiles. The Forestry Chronicle 79:685-691.

British Columbia Ministry of Forests. 1995. Bark beetle management guidebook (Forest Practices Code). Forest Practices Branch, Victoria, British Columbia. 45 p.

Cahill, D.B. 1978. Cutting strategies as control measures of the mountain pine beetle in lodgepole pine in Colorado. Pages 188-191 *in* A.A. Berryman, G.D. Amman, and R.W. Stark (editors). Theory and practice of mountain pine beetle management in lodgepole pine forests. Symposium held at University of Idaho, 25-27 April 1978. Moscow, ID, US.

Carroll, A.L.; Taylor, S.W.; Régnière, J.; Safranyik, L. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Pages 223-232 *in* T.L. Shore, J.E. Brooks, J.E. Stone (editors). Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. Victoria, B.C. Information Report BC-X-399. 298 p.

Carroll, A.L.; Shore, T.L.; Safranyik, L. 2006. Direct control: Theory and practice. Page 304 *in* L. Safranyik and W.R. Wilson (editors). The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C., Canada.

Ciesla, W.M. 2000. Remote sensing in forest health protection. USDA Forest Service, Fort Collins, CO., FHTET Report No. 00-03.

Clarke, S.R.; Billings, R.F. 2003. Analysis of the southern pine beetle suppression program on the national forests in Texas in the 1990s. Journal of Forestry 27(2):122-129.

Cole, W.E.; Cahill, D.B. 1976. Cutting strategies can reduce probabilities of mountain pine beetle epidemics in lodgepole pine. Journal of Forestry 74:294-297.

Cole, W.E.; Cahill, D.B.; Lessard, G.D. 1983. Harvesting strategies for management of mountain pine beetle infestations in lodgepole pine: preliminary evaluation, East Long Creek demonstration area, Shoshone National Forest, Wyoming. USDA Forest Service, Intermountain Research Station, Research Paper INT-318, p 11.

Cole, W.E.; McGregor, M.D. 1985. Reducing or preventing mountain pine beetle outbreaks in lodgepole pine stands by selective cutting. Pages 175-185 *in* L. Safranyik (editor). IUFRO Working Parties S2.07-05 and S2.07-06 Symposium: The Role of the Host in the Population Dynamics of Forest Insects. 4-7 September 1983, Banff, Alberta. Canadian Forestry Service, Pacific Forest Research Centre, Victoria, B.C.

Coops, N.C.; Culvenor, D.; Preston, R.; Catling, P.C. 1998. Procedures for predicting habitat and structural attributes in eucalypt forests using high spatial resolution remotely sensed imagery. Australian Forestry 61:244-252.

Coops, N.C.; Johnson, M.; Wulder, M.A.; White, J.C. 2006a. Assessment of QuickBird high spatial resolution imagery to detect red attack damage due to mountain pine beetle infestation. Remote Sensing of Environment 103:67-80.

Coops, N.; Wulder, M.; White, J. 2006b. Integrating remotely sensed and ancillary data sources to characterize a mountain pine beetle infestation. Remote Sensing of Environment 105:83-97.

Eaton, C.B. 1941. Influence of the mountain pine beetle on the composition of mixed pole stands of ponderosa pine and white fir. Journal of Forestry 39:710-713.

Fettig, C.J.; McMillin, J.D.; Anhold, J.A.; Hamud, S.M.; Borys, R.R.; Dabney, C.P.; Seybold, S.J. 2006. The effects of mechanical fuel reduction treatments on the activity of bark beetles (Coleoptera: Scolytidae) infesting ponderosa pine. Forest Ecology and Management 230:55-68.

Fettig, C.J.; Klepzig, K.D.; Billings, R.F.; Munson, A.S.; Nebeker, T.E.; Negrón, J.F.; Nowak, J.T. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle outbreaks in coniferous forests of the western and southern United States. Forest Ecology and Management 238:24-53.

Franklin, S.; Wulder, M.; Skakun, R.; Carroll, A. 2003. Mountain pine beetle red attack damage classification using stratified Landsat TM data in British Columbia, Canada. Photogrammetric Engineering and Remote Sensing 69:283-288.

Gimbarzevsky, P. 1984. Remote sensing in forest damage detection and appraisal – selected annotated bibliography. Canadian Forestry Service, Victoria, Information Report BC-X-253.

Hall, R.W. 1984. Effectiveness of insecticides for protecting ponderosa pines from attack by red turpentine beetle (Coleoptera: Scolytidae). Journal of Economic Entomology 77:446-448.

Hall, P.M. 2004. Provincial bark beetle strategy: Technical implementation guidelines. Pages 67-75 *in* T.L. Shore, J.E. Brooks, and J.E. Stone (editors). Proceedings of the Mountain Pine Beetle Symposium: Challenges and Solutions. October 30-31, 2003, Kelowna, British Columbia, Canada. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, B.C. 298 p.

Hall, R.W.; Shea, P.J.; Haverty, M.I. 1982. Effectiveness of carbaryl and chlorpyriphos for protecting ponderosa pine trees from attack by the western pine beetle (Coleoptera: Scolytidae). Journal of Environmental Entomology 75:504-508.

Hamel, D.R. 1978. Results of harvesting strategies for management of mountain pine beetle infestations in lodgepole pine on the Gallatin National Forest, Montana. Pages 192-196 *in* A.A. Berryman, G.D. Amman, and R.W. Stark (editors). Theory and practice of mountain pine beetle management in lodgepole pine forests. Proceedings 25-27 April 1978, Pullman, WA. University of Idaho, USDA Forest Service, Ogden, UT and Washington D.C.

Haverty, M.I.; Shea, P.J.; Wenz, J.M. (1996) Metasystox-R, applied in mauge injectors, ineffective in protecting individual ponderosa pines from western pine beetle. Research Note PSW-RN-420, Pacific Southwest Research Station, USFS, 8 p.

Haverty, M.I.; Gibson, K.E.; Hoffman, J.T.; Shea, P.J.; Wenz, J.M. 1998. Effectiveness of esfenvalerate, cyfluthrin, and carbaryl in protecting individual lodgepole pines and ponderosa pines from attack by Dendroctonus spp. Research Paper PSW-RP-237, Pacific Southwest Research Station, USFS, 12 p.

Hawthorn, D.; Kirik, M.; Eagles, P.F. 2002. Evaluating management effectiveness of parks and park systems: a proposed methodology. Pages 414-430 *in* S. Bondrup-Nielsen, N.W. Munro, G. Nelson, J.H.M. Willison, T.B. Herman, and P. Eagles (editors). Managing Protected Areas in a Changing World: Proceedings of the Fourth International Conference on Science and Management of Protected Areas. Science and Management of Protected Areas Association, Wolfville, Nova Scotia.

Hayes, J.L.; Strom, B.L.; Rotom, L.M.; Ingram, L.L. Jr. 1994. Repellent properties of the host compound 4-allylanisole to the southern pine beetle. Journal of Chemical Ecology 20:1595–1615.

Henigman, J.; Ebata, T.; Allen, E.; Holt, J.; Pollard, A., editors. 1999. Field guide to forest damage in British Columbia. British Columbia Ministry of Forests Victoria, British Columbia, Canada.

Hindmarch, T.D.; Reid, M.L. 2001. Thinning of mature lodgepole pine stands increases beetle abundance and diversity. Canadian Journal of Forest Research 31:1502-1512.

Huber, D.P.W.; Borden, J.H. 2001. Protection of lodgepole pines from mass attack by mountain pine beetle, *Dendroctonus ponderosae*, with nonhost angiosperm volatiles and verbenone. Entomologia Experimentalis et Applicata 99:131-141.

Johnstone, W.D. 2002. Thinning lodgepole pine in southeastern British Columbia (EP 384/385): 46-year results. B.C. Ministry of Forests, Victoria. Working Paper 63.

Kegley, S.; Gibson, K. 2004. Protecting whitebark pine trees from mountain pine beetle attack using verbenone. USDA Forest Service, Forest Health Protection. Report 04-8. Missoula, MT. 4 p.

Kneppeck, I.D.; Ahern, F.J. 1989. A comparison of images from a pushbroom scanner with normal color aerial photographs for detecting scattered recent conifer mortality. Photogrammetric Engineering and Remote Sensing 55:333-337.

Kostyk, B.C.; Borden, J.H.; Gries, G. 1993. Photoisomerism of antiaggregation pheromone verbenone: Biological and practical implications with respect to the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera:Scolytidae). Journal of Chemical Ecology 19:1749-1759.

Langor, D.W. 2003. Mountain pine beetle. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Forest Leaflet 36.

McGregor, M.D.; Amman, G.D.; Schmitz, R.F.; Oakes, R.D. 1987. Partial cutting lodgepole pine stands to reduce losses to the mountain pine beetle. Canadian Journal of Forest Research 17:1234-1239.

Mitchell, R.G.; Waring, R.H.; Pitman, G.B. 1983. Thinning lodgepole pine increases tree vigor and resistance to Mountain Pine Beetle. Forest Science 29:204–211.

Nelson, T.; Wulder, M.; Niemann, K.O. 2001. Spatial resolution implications of digitising aerial photography for environmental applications. The Journal of Imaging Science 49:223-232.

Nelson, T.; Boots, B.; White, K.J.; Smith, A.C. 2006. The impact of treatment on mountain pine beetle infestation rates. BC Journal of Ecosystems and Management 7:20-36.

Noss, R. F.; Cooperrider, A.Y. 1994. Saving Nature's Legacy. Island Press, Washington D.C. 416 pp.

Parker, T.J.; Clancy, K.M.; Mathiasen, R.L. 2006. Interactions among fire, insects and pathogens in coniferous forests of the interior western United States and Canada. Agricultural and Forestry Entomology 8:167-189.

Payne, T.L.; Billings, R.F. 1989. Evaluation of s-verbenon applications for suppressing southern pine beetle (Coleoptera: scolytidae) infestations. Journal of Economic Entomology 82:1702-1708.

Pomeroy, R.S.; Parks, J.E.; Watson, L.M. 2004. How is your MPA doing? A guidebook of natural and social indicators for evaluating marine protected area management effectiveness. IUCN. Gland, Switzerland.

Puritch, G.S. 1981. Nonvisual remote sensing of trees affected by stress: A review. Canadian Forestry Service, Victoria, B.C. Forestry Technical Report BC-X-30.

Roberts, A.; Dragicevic, S.; Northrup, J.; Wolf, S.; Li, Y.; Coburn, C. 2003. Mountain pine beetle detection and monitoring: Remote sensing evaluations. Forestry Innovation Investment Operational Research Report. Recipient Agreement R2003-0205.

Roe, A.L.; Amman, G.D. 1970. The mountain pine beetle in lodgepole pine forests. USDA Forest Service, Intermountain Forest and Range Experiment Station. Research Paper INT-71, 23 p.

Safranyik, L.; Linton, D.A.; Shore, T.L.; Hawkes, B.C. 2001. The effects of prescribed burning on mountain pine beetle in lodgepole pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Information Report BC-X-391. 9 p.

Schmidt, W.C.; Alexander, R.R. 1985. Strategies for managing lodgepole pine. Pages 201-210 *in* D.M. Baumgartner, R.G. Krebill, J.T. Arnott, G.F. Weetman (editors). Lodgepole: The species and its management. Symposium proceedings. 8-10 May 1984, Spokane, WA; 14-16 May 1984, Vancouver, Office of Conferences and Institutes Cooperative Extension, Pullman, WA.

Schmitz, R.F.; 1988. Efficacy of verbenone for preventing infestation of high-value lodgepole pine stands by the mountain pine beetle. Pages 75-79 *in* G.D. Amman (editor). Proceedings - Symposium on the Management of Lodgepole Pine to Minimize the Losses to the Mountain Pine Beetle. Kalispell, MT, 12-14 July 1988.

Schmitz, R.F.; McGregor, M.D.; Amman, G.D.; Oakes, R.D. 1989. Effect of partial cutting treatments of lodgepole pine stands on the abundance and behavior of flying mountain pine beetles. Canadian Journal of Forest Research 19:566-574.

Shea, P.J.; Haverty, M.I.; Hall, R.C. 1984. Effectiveness of fenitrothion and permethrin for protecting ponderosa pine trees from attack by the western pine beetle. Journal of Georgia Entomological Society 19:427-433.

Shea, P.J.; McGregor, M.D.; Daterman, G.E. 1992. Aerial application of verbenone reduces attack of lodgepole pine by mountain pine beetle. Canadian Journal of Forest Research 22:436-441.

Shore, T.L.; Safranyik,L.; Lindgren, B.S. 1992. The response of mountain pine beetle (*Dendroctonus ponderosae*) to lodgepole pine trees baited with verbenone and exo-brevicomin. Journal of Chemical Ecology 18:533-541.

Skakun, R.S.; Wulder, M.A.; Franklin, S.E. 2003. Sensitivity of the Thematic Mapper Enhanced Wetness Difference Index (EWDI) to detect mountain pine needle red attack damage. Remote Sensing of Environment 86:433-443.

Stem, C.; Margoluis, R.; Salafsky, N.; Brown, M. 2005. Monitoring and evaluation in conservation: A review of trends and approaches. Conservation Biology 19:295-310.

Stjernberg, E. 2004. Review and synthesis of historical adaptive management strategies to control mountain pine beetle (*Dendroctonus ponderosae*): Efficacy and economics. Mountain Pine Beetle Initiative Project #3.02 Summary Report. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC.

Strahler, A.H.; Woodcock, C.E.; Smith, J.A. 1986. On the nature of models in remote sensing. Remote Sensing of Environment 20:121-139.

Stock, A.J.; Gorley, R.A. 1989. Observations on a trial of broadcast burning to control an infestation of the mountain pine beetle *Dendroctonus ponderosae*. The Canadian Entomologist 121:521-523.

Stolton, S.; Hockings, M.; Dudley, N.; MacKinnon, K.; Whitten, T. 2003. Reporting progress in protected areas. A site-level management effectiveness tracking tool. World Bank, WWF Alliance. Washington, DC.

Strom, B.L.; Roton, L.M.:, Goyer, R.A.; Meeker, J.R. 1999. Visual and semiochemical disruption of host finding in the southern pine beetle. Ecological Applications 9:1028 – 1038.

Strom, B.L.; Goyer, R.A.; Shea, P.J. 2001. Visual and olfactory disruption of orientation by the western pine beetle to attractant-baited traps. Entomologia Experimentalis et Applicata 100:63 – 67.

Waring, R.H.; Pitman, G.B. 1980. A simple model for host resistance to bark beetles. Oregon State University School of Forest Research Laboratory Research Note.

Werner, R.A.; Holsten, E.H. 1992. Effectiveness of sevin with and without diesel for remedial control of spruce beetles (Coleoptera: Scolytidae) in infested spruce in Alaska. Journal of Economic Entomology 85:473-476.

Westfall, J. 2007. Summary of forest health conditions in British Columbia. Ministry of Forests, Forest Practices Branch, Victoria, British Columbia, Canada. 49 p.

White, J.C.; Wulder, M.A.; Brooks, D.; Reich, R.; Wheate, R. 2005. Mapping mountain pine beetle infestation with high spatial resolution satellite imagery. Remote Sensing Environment 96:240-251.

White, J.C.; Wulder, M.A.; Grills, D. 2006. Detecting and mapping mountain pine beetle red attack damage with SPOT-5 10-m multispectral imagery. BC Journal of Ecosystems and Management 7: 105-119.

White, J.C.; Coops, N.C.; Hilker, T.; Wulder, M.A.; Carroll, A.L. 2007. Detecting mountain pine beetle red attack damage with EO-1 Hyperion moisture indices. International Journal of Remote Sensing 28:2111-2121.

Whitehead, R.J.; Safranyik, L.; Russo, G.L.; Shore, T.L.; Carroll, A.C. 2004. Silviculture to reduce landscape and stand susceptibility to mountain pine beetle. Pages 233-344 *in* T.L. Shore, J.E. Brooks, and J.E. Stone (editors). October 30-31, 2003, Kelowna, British Columbia. Challenges and Solutions: Proceedings of the Mountain Pine Beetle Symposium. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399. 298 p.

Whitehead, R.J.; Russo, G.L. 2005. "Beetle-proofed" lodgepole pine stands in interior British Columbia have less damage from mountain pine beetle. Natural Resources Canada, Canadian Forest Service, Victoria, B.C. Information Report BC-X-402. 17 p.

Woodcock, C.E.; Strahler, A.H. 1987. The factor of scale in remote sensing. Remote Sensing of Environment 21:311-332.

Wulder, M.A.; Dymond, C.C.; Erickson, B. 2004a. Detection and monitoring of the mountain pine beetle. Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia. Information Report BC-X-398.

Wulder, M.A.; Hall, R.; Coops, N.; Franklin, S. 2004b. High spatial resolution remotely sensed data for ecosystem characterization. Bioscience 54(6):1-11.

Wulder, M.A.; Dymond, C.C.; White, J.C.; Leckie, D.G.; Carroll, A.L. 2006a. Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. Forest Ecology and Management 221:27-41.

Wulder, M.A.; White, J.C.; Bentz, B.J.; Ebata, T. 2006b. Augmenting the existing survey hierarchy for mountain pine beetle red-attack damage with satellite remotely sensed data. The Forestry Chronicle 82:187-202.

Wulder, M.A.; White, J.C.; Bentz, B.; Alvarez, M.F.; Coops, N.C. 2006c. Estimating the probability of mountain pine beetle red attack damage. Remote Sensing of Environment 101:150-166.

Zhang, Q.; Schlyter, F. 2004. Olfactory recognition and behavioural avoidance of angiosperm nonhost volatiles by conifer-inhabiting bark beetles. Agricultural and Forest Entomology 6:1-19.

Table 1. Framework developed by the World Commission on Protected Areas (WCPA), a branch of The World Conservation Union (IUCN), for assessing management effectiveness of both protected areas and protected area systems (Stolton et al. 2003). The framework is applied within the context of efficacy monitoring of mountain pine beetle (MPB) mitigation approaches.

Elements of Evaluation	Explanation	Criteria that are assessed	Focus of evaluation	MPB Context
Context	***Where are we now?*** Assessment of importance, threats and policy environment.	Significance; Threats; Vulnerability; National context; Partners	Status	Status of existing forest (forest inventory) Survey extent and severity of MPB damage
Planning	***Where do we want to be?*** Assessment of design and planning	Legislation and policy; System design; Management planning	Appropriateness	Endemic population levels
Inputs	***What do we need?*** Assessment of resources needed to carry out management	Resourcing of agency; resourcing of site	Resources	Reconnaissance and detailed survey costs Treatment costs
Processes	***How do we go about it?*** Assessment of the way in which management is conducted	Suitability of management processes	Efficiency and appropriateness	Strategic – Landscape level management (e.g. Provincial Bark Beetle Strategy) Tactical - Management unit (e.g. Beetle Management Units) Operational – Stand level (e.g. Forest Practices Code)
Outputs	***What were the results?*** Assessment of the implementation of management programs and actions; delivery of products and services	Results of management actions; services and products	Effectiveness	Survey extent and severity of MPB damage
Outcomes	***What did we achieve?*** Assessment of the outcomes and the extent to which they achieved objectives	Impacts: effects of management in relation to objectives	Effectiveness and Appropriateness	Decreasing G:R Decrease in area impacted by MPB

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